Author response to Anonymous Referee 1 for "Brief Communication: An Electrifying Atmospheric River: Understanding the Thunderstorm Event in Santa Barbara County during March 2019" by Deanna Nash and Leila M.V. Carvalho.

Responses to reviewer comments are given in blue text. New or changed text is given in *italics* (***bold italics*** for emphasis where noted)

General Comments

This brief manuscript describes meteorological characteristics of an atmospheric river event from March 2019 that caused an unprecedented amount of lightning in Santa Barbara. The manuscript is clearly written, and the analysis is straightforward: brief but appropriate for publication as a brief communication. My biggest concern with the manuscript in its present form is that, while the exceptional nature of the amount of lightning is well described and detailed, the links between the meteorology and lightning itself are presumed and not very clearly described. The manuscript also restates the lightning results a bit more than necessary given the (very short) length of the Manuscript.

We thank the reviewer for the time taken to review this manuscript and all constructive feedback that helped improve the paper, specifically in regard to clarifying the links between the lightning and thermodynamics. Below we address the specific comments.

Specific Comments

L. 7-8, 41-43, and 70-71: This result (i.e., the average flash density for the region) is restated three times by the fourth page of the manuscript. Redundancies such as this example are not warranted in such a brief manuscript, and the text should be tightened up to remove them. The text of the abstract needs particular attention to ensure it conveys the most salient results of the manuscript: I suggest removing this peripheral detail in favor of an additional sentence at the end of the abstract that links the meteorology with the exceptional lightning.

We agree with the reviewer and have updated these sections to remove the redundancies. The final sentence of the abstract now states, *"Despite the negligible convective available potential energy (CAPE) during the peak of the thunderstorm near Santa Barbara, the lifting of layers with high water vapor content in the AR via warm conveyor belt and orographic forcing in a convectively unstable atmosphere resulted in the formation of hail and enhanced electrification."*

L. 111-112: It's rather difficult to see this synoptic feature (WCB) with such a zoomed-in domain.

We agree it was difficult to see the WCB in the previous version of the figure. We have zoomed out on the domain of Fig. S3 and have added contours of IVT to the maps for reference to the location of the AR in relation to the WCB (noted by RC2). See below for updated Fig. S3

L. 147-150 and much of this entire section: Much of this text relays presumptions as conclusions. For example, 'The convective updraft in the lower troposphere was very important for the onset of electrification,...' this manuscript in no way proves what was or wasn't important for the onset of electrification (instead it presents the meteorology, documents that there was quite a lot of electrical activity, and requires inference between the two). This section needs revision to clarify what previous literature suggests are important factors for lots of lightning in storms, and how those factors relate to this particular storm. I was unable to read the citation Price 2013 from the manuscript, but found Pessi and Businger (2009) helpful in framing my review.

We agree that clarification was needed between what previous literature suggests are important factors in electrification and what the data implies about the electrification for this particular storm. We thank the reviewer for suggesting the reference Pessi and Businger (2009) which was added to this manuscript. The section on lightning conditions in the results has been edited extensively for these clarifications.

L. 193-203: This summary paragraph could do a better job relating what was unusual about this atmospheric river (AR) event that potentially led it to produce so much lightning. ARs in particular are not terribly unusual for Santa Barbara (e.g. Rutz et al. 2014). In addition, the authors suggest that the 2.5km 0 degree C isotherm was a large factor in allowing hail to develop, but 2.5 km is not a particularly low freezing level for a midlatitude storm at this latitude (Cannon et al. 2017). More care and thought should be put toward this aspect of the manuscript; without this connection the main emphasis of the manuscript becomes a bit fuzzy. The dry air layer at 250 hPa is alluded to as a possible mechanism (and note there is another dry layer at 500 hPa).

According to Rutz et al. (2014), AR frequency in the Santa Barbara coastal region is approximately 6% of the time steps in ERA-Interim analyses (see Rutz et al. (2014) Fig 4a) between November 1988 to April 2011 (Nov-April only), meaning that an AR was identified at approximately 1,000 6-hour time steps or roughly 250 AR days out of 4,100. The global AR detection algorithm developed by Guan and Waliser (2015) used to identify previous AR days in our study shows similar agreement to the results of Rutz et al. (2014). We think that 6% of the time is a relatively infrequent occurrence for ARs, and Southern California has the lowest frequency of ARs compared to other regions along the west coast of North America (Harris and Carvalho, 2018; Guan and Waliser, 2015, among others) However, our manuscript shows that despite the AR having a relatively average IVT value for ARs that make landfall in Santa Barbara (around 400 kg m^{-1} s^{-1}; see Fig. S2b), when looking at the vertical profile of the horizontal water vapor flux at each pressure level, the AR that occurred on 5-6 March 2019 had a significantly above average water vapor flux content in the middle troposphere compared to the other 170 days and AR made landfall in Santa Barbara during the month of March (see Fig. 3c). To show what was unique and what was not for this particular AR, we have updated Fig. S2 to include distribution information of the characteristics of ARs in Santa Barbara, including 0°C Isotherm Height.

According to Cannon et al. (2017), the mean height of the 0°C isotherm was about 2,500 m for the 83 AR events in Central and Northern California (20°N to 60°N and 160°W to 110°W) during three winter seasons (October through March; 2014-2017). After calculating the height of the 0°C isotherm using MERRA2 and the methodology used in Cannon et al. (2017) and Harris Jr et al. (2000), we created a climatology of the 0°C isotherm for all days an AR made landfall in Santa Barbara (identified using the AR detection algorithm provided by Guan and Waliser (2015)) between 1980 and 2017 (n=1814), and found that the average height of the 0°C isotherm during these days was about 3500 m (Fig. S2d). Therefore, the 0°C isotherm during the 5 March AR was below average for the location and the period.

We do agree with the reviewer that the connection between the meteorological conditions and the lightning could be improved to demonstrate the reasons for the unusual lightning strikes. To properly address these issues we included new results regarding the profile of convective (potential) instability in the location of the highest lightning flash density (see new Fig. S4), identified by the profiles of Equivalent Potential Temperature (θ_E). We have also added the θ_E profile to Fig. 3 to indicate the importance of convective instability in Santa Barbara at the time of the peak of the event (see Fig. 3b). With this information we provided additional evidence that the deep moist atmosphere lifted via WCB and orographic forcing in a convectively unstable atmosphere with a low 0°C isotherm was highly conducive to hail formation and lightning, even under conditions of relatively low CAPE.

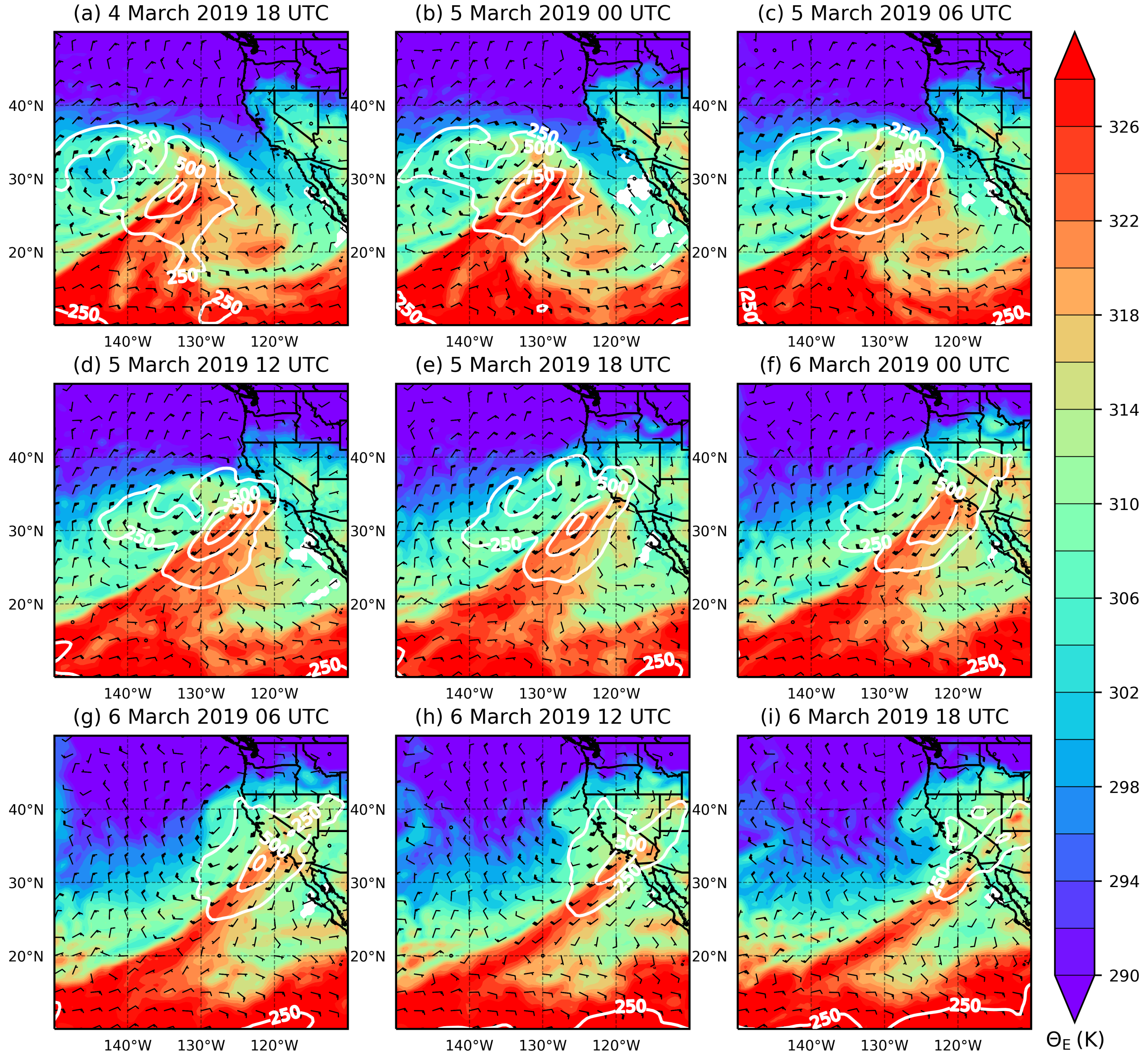

Figure 1. Figure S3. CFSv2 850 hPa Equivalent Potential Temperature (shaded; K), 850 hPa winds (barbs; knots), and IVT greater than 250 kg m^{-1} s^{-1} (white contours; every 250 kg m^{-1} s^{-1}) for each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC.

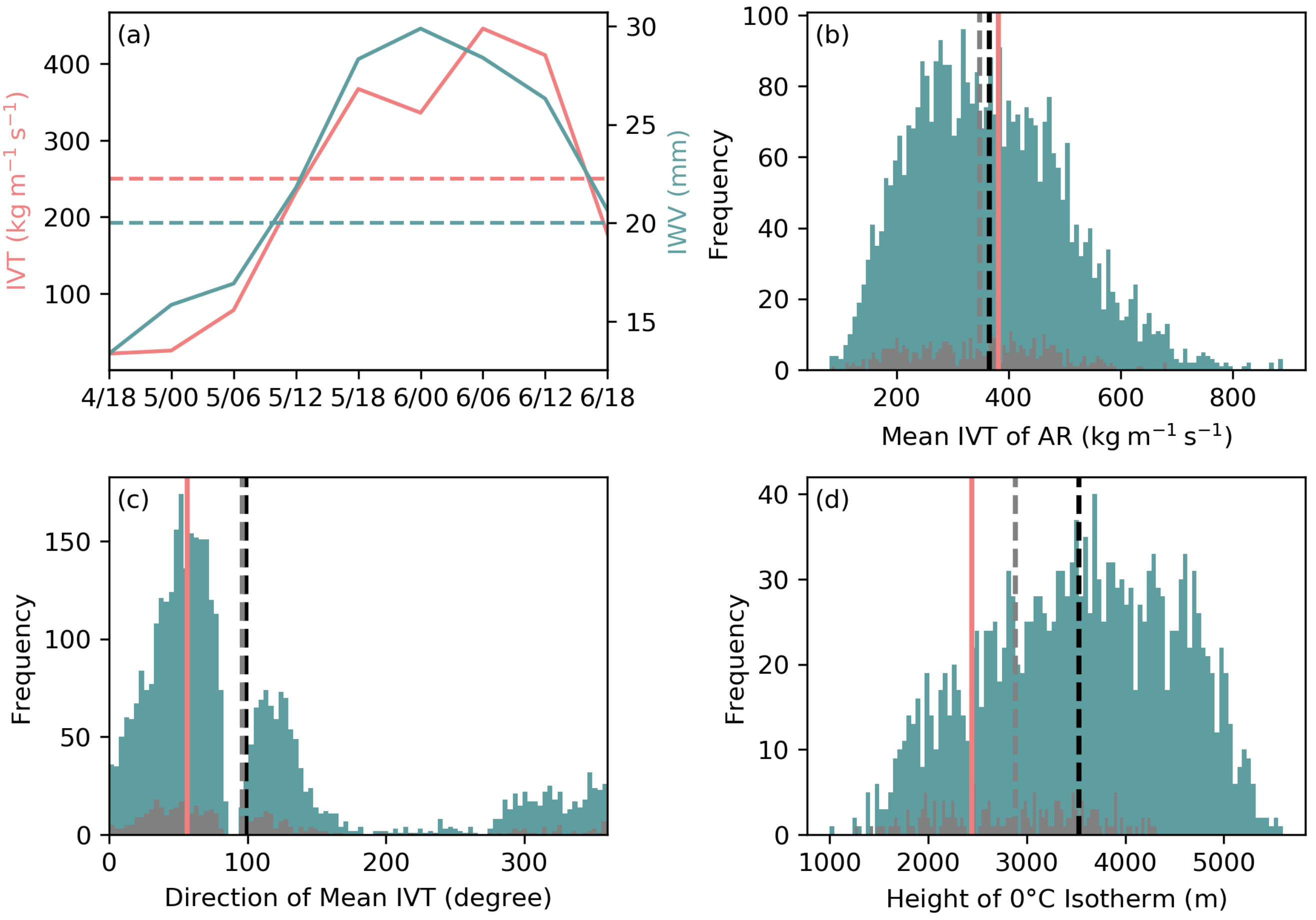

Figure 2. Figure S2. (a) CFSv2 IVT (red line; kg m^{-1} s^{-1}) and IWV (blue line; mm) at the grid cell closest to Santa Barbara (34.5°N, 119.5°W) at each 6-hour time step between 4 March 2019 18 UTC and 6 March 2019 18 UTC. The minimum thresholds for the location to be considered part of an AR event are indicated by the dotted lines. (b) Mean IVT of the AR objects that made landfall in Santa Barbara in all the months (blue lines) and only March (grey lines) between January 1980 and May 2019 based on the AR Catalog from Guan and Waliser (2015). The mean IVT for the AR Event on March 5 is shown by the red solid line. The means of the distributions are shown in the dotted line. (c) Same as (b) but for direction of mean IVT propagation (azimuth is 0°if IVT is directed to the north). (d) Same as (b) but for the height of the 0°C Isotherm (m) interpolated from MERRA2 temperature and geopotential height.

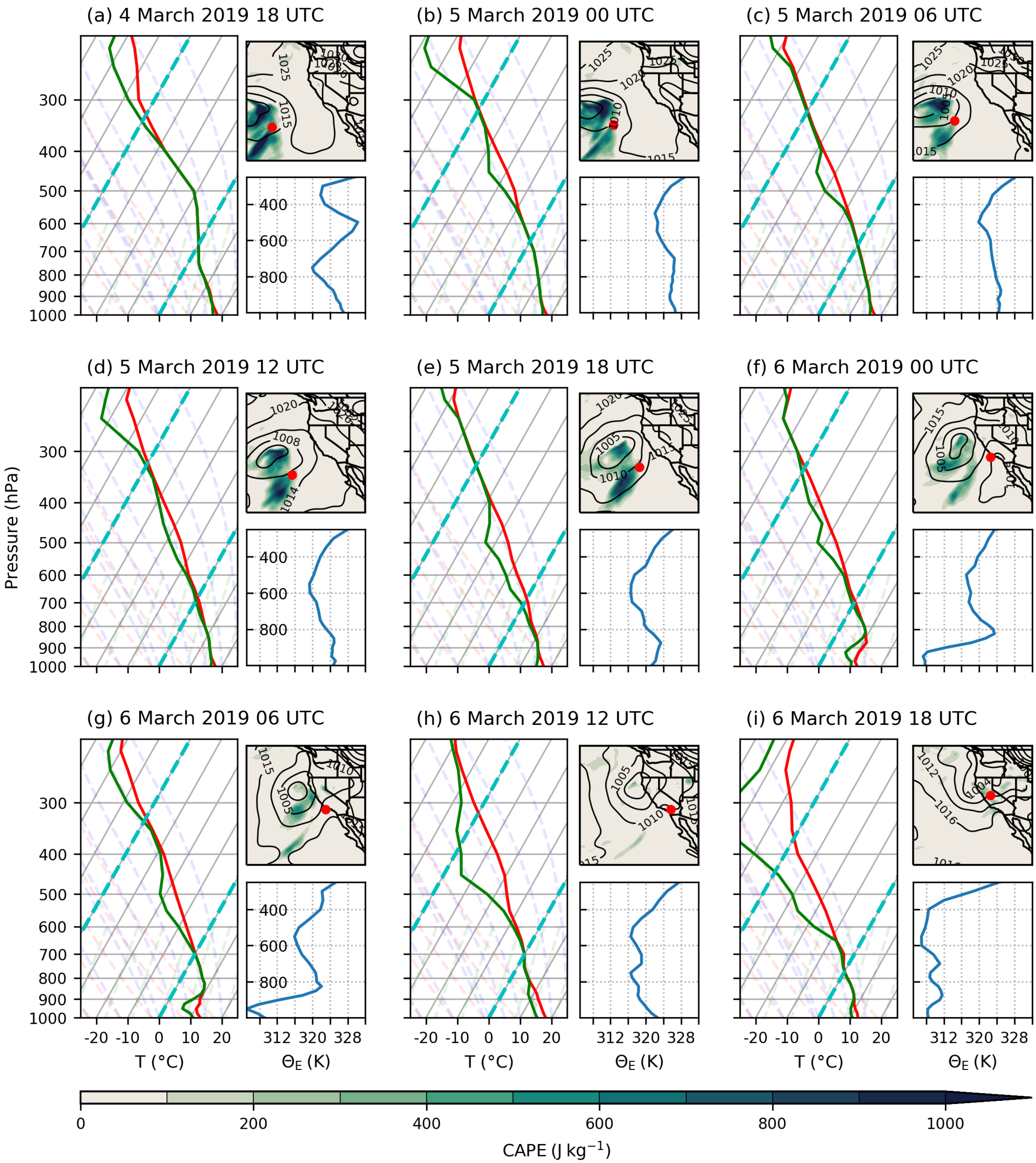

Figure 3. Figure S4. *(left panel)* Skew(t) - log(p) vertical profile of CFSv2 temperature (red line) and dew point (green line) at the grid cell with the highest flash density (per 6 hours); *(right top panel)* CFSv2 CAPE (shaded, J kg^{-1}) and MSLP (black dashed contours; hPa) with the location of the highest flash density indicated by the red dot; *(right bottom panel)* CFSv2 Equivalent Potential Temperature (blue line; K) at the grid cell with the highest flash density for each 6-hour time step between (a) 4 March 2019 18 UTC and (i) 6 March 2019 18 UTC.

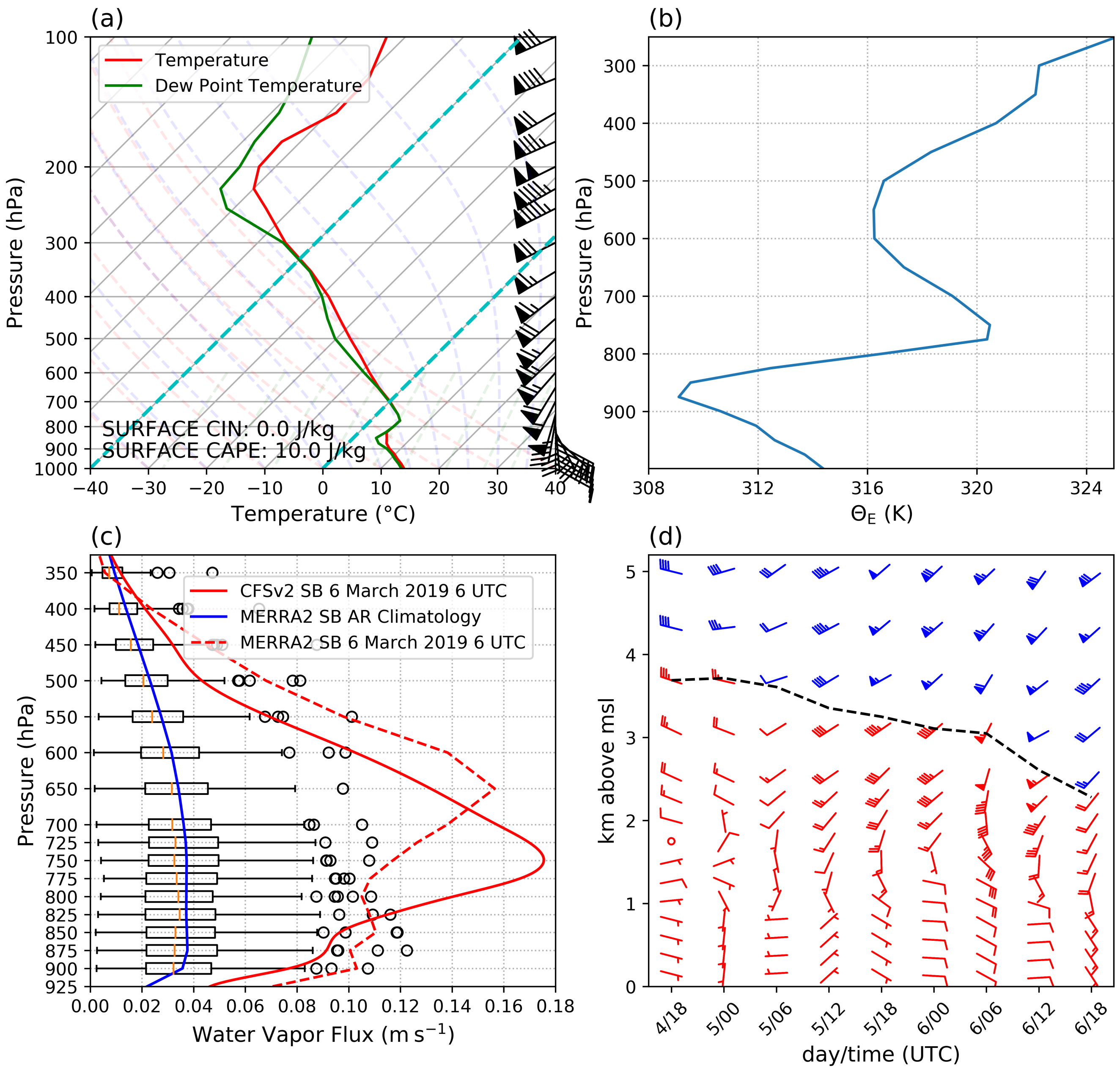

Figure 4. Figure 3. (a) Skew(t) - log(p) vertical profile of CFSv2 temperature (red line) and dew point (green line) at 34.5°N and 119.5°W at 6 March 2019 06 UTC. CFSv2 winds (knots; barbs) are indicated on the right side of the figure for each vertical level. Surface values of CAPE and Convective Inhibition (CIN) are shown in the bottom left corner. (b) CFSv2 Equivalent Potential Temperature θ_E (blue line; K) at 34.5°N and 119.5°W at 6 March 2019 06 UTC. (c) Climatological vertical profile of horizontal water vapor flux (m s^{-1}) based on MERRA2 at 34.5°N, 119.375°W for all days when AR conditions are met during the month of March between 1980 and 2015 (i.e. IVT >= 250 kg m^{-1} s^{-1}) at this location (blue line and box and whisker plots show the distribution of the 170 events), and vertical profile of horizontal water vapor flux (m s^{-1}) based on CFSv2 (red solid line) and MERRA2 (red dashed line) at the same location at 6 March 2019 06 UTC. (d) CFSv2 winds (knots, barbs) at vertical levels (km above mean sea level) at 34.5°N and 119.5°W at 6-hour intervals from 4 March 2019 18 UTC to 6 March 2019 18 UTC. The temperature (°C) is indicated by the color of the barb. Red barbs mean the temperature was greater than 0°C and blue barbs mean the temperature was less than 0°C. The height of the 0°C isotherm is indicated by the black dashed line.

References

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